Modeling Biomass Gasification in Circulating Fluidized Beds: Model Sensitivity Analysis

Qi Miao[a], Jesse Zhu*[a], Shahzad Barghi[a], Chuangzhi Wu[b], Xiuli Yin[b], Zhaoqiu Zhou[b]

[a]Particle Technology Research Centre, University of Western Ontario, London, Canada N6A 5B9

[b]CAS Key Laboratory of Renewable Energy and Gas Hydrate, Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, Guangzhou 510640, China

jzhu@uwo.ca

Abstract

A sensitivity analysis was performed on the 1-dimensional biomass gasification model developed by Miao et al. (2013) [Miao, Qi et al., "Modeling biomass gasification in circulating fluidized beds." Renewable Energy 50 (2013): 655-61] to test its response to several gasifier operating conditions including equivalence ratio (ER), bed temperature, fluidization velocity, biomass feed rate and moisture content. The parameters for the gasifier performance included syngas composition, lower heating value (LHV) and production rate, gasification efficiency as well as overall carbon conversion. The model sensitivity analysis showed that ER, bed temperature, fluidization velocity, biomass feed rate and moisture content had various effects on the gasifier performance. However, the model was more sensitive to variations in ER and bed temperature.

Keywords

Equivalence Ratio; Temperature; Feed Rate; Moisture; Syngas Composition; LHV; Gasification Efficiency; Carbon Conversion; Sensitivity Analysis

Introduction

Mansaray et al. (2000) developed a mathematical model of a fluidized bed rice husk gasifier and tested the model sensitivity using ASPEN PLUS. It was concluded that the fluidization velocity, equivalence ratio, oxygen concentration in fluidizing gas, and moisture content in rice husk had dramatic effects on the gasifier performance. However, it failed to estimate the effect of biomass feed rate on the gasifier performance. Sadaka et al. (2002) developed a two phase biomass air-steam gasification model for fluidized bed reactors and performed a sensitivity analysis to test its response to variations in fluidization velocity, steam flow rate and biomass to steam ratio. The results showed that the model was sensitive to changes in all operating parameters. However, it didn't analyse the effects of operating conditions on gasification efficiency and overall carbon conversion. Sanz and Corella (2006) developed a 1-dimensional and semirigorous model for atmospheric and circulating fluidized bed biomass gasifiers and gave details of the effects of total ER, 2rd air, biomass moisture and flowrate on the gasifier performance. They concluded the parameters with the biggest influence on gas composition and gas quality are ER, percentage of 2nd air flow and biomass moisture. Biomass flowrate has an important influence on gas quality but not so important for gas composition. 2nd air inlet height does not have an important effect.

In our previous study in Miao et al. (2013), a 1-dimensional mathematical model was developed for circulating fluidized bed biomass gasifiers (CFBBGs). This model integrates several aspects of the biomass gasification process, including hydrodynamics, chemical reaction kinetics, heat and mass balances, etc and is capable of predicting the bed temperature, syngas compositions and LHV, gasification efficiency, carbon conversion as well as gas production rate over a wide range of operating conditions. The validation of the model showed that the preliminary evaluation of the model prediction was in a reasonably good agreement with the results obtained experimentally, except for CO_2 concentration in the exit syngas, which was slightly over-predicted by the model. It is therefore necessary to test the sensitivity of the model to variations in the parameters which most likely influence the gasifier performance. In addition, more comparisons of the model prediction to the real experimental results as well as optimization are the subject of the next paper.

The goal of this study was to test the sensitivity of the model predictions on syngas compositions and LHV, gasification efficiency, carbon conversion and gas production rate by investigating the influence of ER (the ratio of air flow to the airflow required for stoichiometric combustion of the biomass, which indicates extent of partial combustion), bed

temperature, fluidization velocity, biomass feed rate and moisture content on the gasifier performance.

Model Description

The model developed in the previous study is a one-dimensional comprehensive model, capable of predicting the performance of CFBBGs at steady state operations. The mass and energy balances as well as CFBBG hydrodynamics were taken into consideration. Because biomass gasification in a CFBG is directly affected by its hydrodynamic parameters, both hydrodynamic and combustion models must be treated simultaneously to yield a predictive model for the CFBBG. The reactor is assumed to be in steady state and only CO, CO_2, H_2, CH_4, and N_2 are considered in the produced dry syngas composition. A reaction network for biomass gasification with air in a CFB has been proposed. Reactions considered in this network include pyrolysis/devolatilization, combustion, char gasification, gas phase reactions, tar cracking, etc. The set of kinetic equations for the reaction network used to calculate the product distribution originates both from our own experimental research and some published papers. Refer to Miao et al. (2013) for a detailed description about the developed model.

Results and Discussion

Effect of Operating Conditions on Axial Bed Temperature Profile

TABLE 1 THE RANGES OF VARIABLES USED IN THE MODEL SENSITIVITY ANALYSIS

ER (-)	Fluidization velocity(m/s)	Biomass feed rate(kg/h)	Moisture content(wt %)
0.15	0.59	1400	12.5
0.20	0.78	1400	12.5
0.25	0.97	1400	12.5
0.30	1.17	1400	12.5
0.35	1.37	1400	12.5
0.25	0.69	1000	12.5
0.25	0.83	1200	12.5
0.25	0.97	1400	12.5
0.25	1.11	1600	12.5
0.25	1.25	1800	12.5
0.25	0.97	1400	7.5
0.25	0.97	1400	10
0.25	0.97	1400	12.5
0.25	0.97	1400	15
0.25	0.97	1400	17.5

The developed model was used to predict the axial bed temperature profiles under various operating conditions. The variables considered are ER, fluidization velocity, biomass feed rate, and biomass moisture content (with 5 levels each). A base case, which represents a typical operating condition of the investigated CFBBG (Wu et al., 2009), was used for each variable and this variable was independently changed around its base value in the range shown in Table 1. Increasing the ER at a fixed biomass feed rate was achieved by changing the inlet air flow rate, which in turn changed the fluidization velocity. Increasing the steam flow rate at fixed fluidization velocity was applied by decreasing the inlet air flow rate. On the other hand, increasing the biomass feed rate at a fixed ER led to an increament of inlet air flow rate.

Figure 1 shows the effect of ER on bed temperature profile. An increase in ER was achieved by adding more air at a constant biomass feed rate. For each ER, the temperature of bottom bed was higher than that of top dilute region. The model results showed that the bed temperature was practically insensitive to ER changes. This could be attributed to the joint effects of ER and fluidization velocity changes. Increasing ER means an increased amount of air introduced into the reactor, which in turn increases the rate of the exothermic reactions (oxidation reactions) and release of energy. On the other hand, a higher ER results in a higher fluidization velocity, which enhances the gas-solid mixing heat transfer, as well reduces the residence time for both gas and particles. Therefore, even though the heat generation had increased, the shorter residence time restricted the relative energy accumulation and thus temperature did not appreciably change. When ER was high, i.e. ER=0.35, the bed temperature decreased slightly at the air inlet and then increased. This might be due to the cooling effect caused by entry of large volume of air.

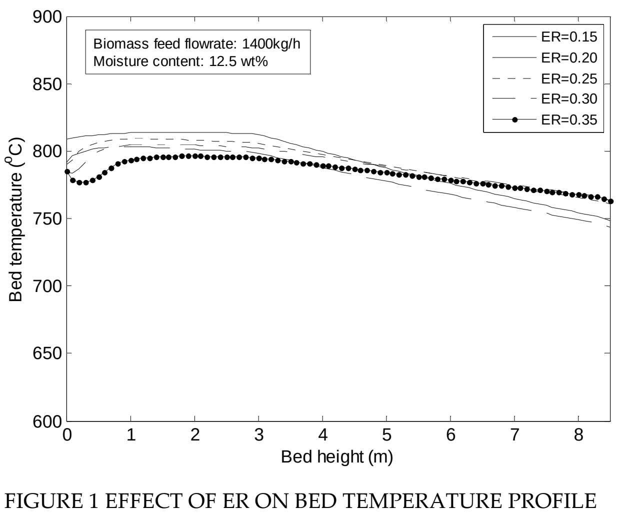

FIGURE 1 EFFECT OF ER ON BED TEMPERATURE PROFILE

Figure 2 depicts the effect of biomass feed rate on bed temperature profile. Gasification air flowrate will

increase accordingly by increasing biomass flowrate at a constant ER. The model results showed that, generally, a faster biomass feeding rate resulted in a lower temperature at the same ER. This was due to the increase in the endothermic reactions, which captured the energy from the bed and also the higher energy requirement to dry and pyrolyse the more biomass. Similar results were reported by Sadaka et al. (2002). Similar to Figure 1, when biomass feed rate was high, i.e. F=1800 kg/h, the bed temperature decreased slightly at the biomass inlet and then increased. This must be due to the cooling effect of large flowrate of cold biomass.

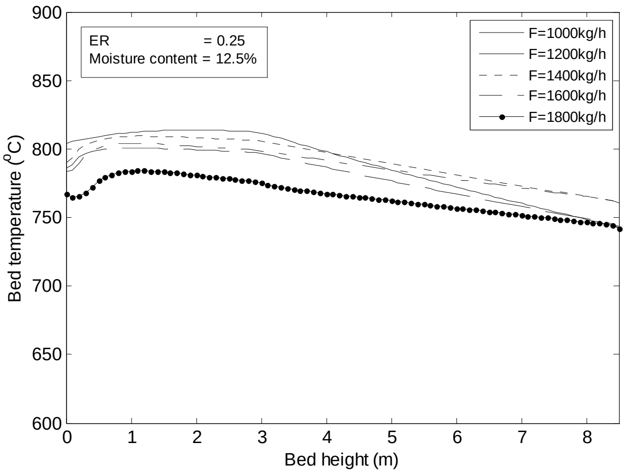

FIGURE 2 EFFECT OF BIOMASS FEED RATE ON BED TEMPERATURE PROFILE

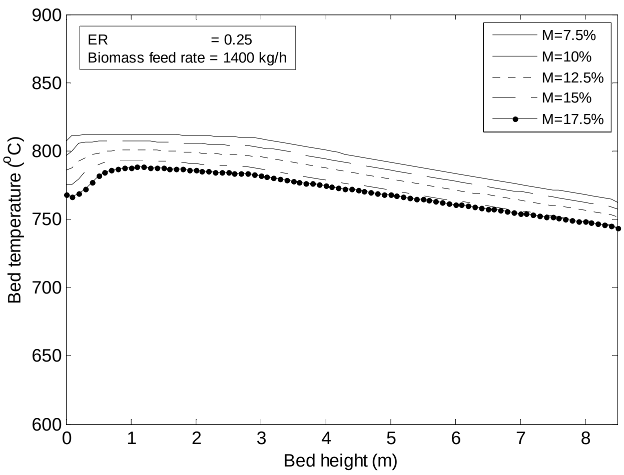

FIGURE 3 EFFECT OF BIOMASS MOISTURE CONTENT ON BED TEMPERATURE PROFILE

Figure 3 shows the effect of biomass moisture content on bed temperature profile. It is obvious that the more moisture content in the biomass, the lower the bed temperature is. This is due to the intensification in endothermic water related gasification reactions (e.g., water gas reaction and CH_4 reforming) and the increased energy required to vaporize the moisture. Similar results were reported by Mansaray et al. (2000).

Effect of Operating Conditions on Syngas Composition

The mole fractions of combustible components (CO, H_2 and CH_4) in syngas determine the quality of syngas, which in turn decide the syngas LHV and gasification efficiency. Figure 4 shows the effect of ER on the mole fractions of syngas. To show clearly the effect of ER separately, an average bed temperature of 800°C was used. The model results indicated that ER had a significant effect on the syngas composition, showing that the higher the ER is, the lower the mole fractions of the combustible gases are. This could be attributed to: (a) the high amount of oxygen introduced to the system which resulted in burning some of the combustible gases and (b) the increases of the mole fractions of the noncombustible components (O_2, N_2 and CO_2) of the producer gas due to the high amount of air being introduced to the system (Raissi and Trezek, 1987; Schoeters et al., 1989; Ergudenler and Ghaly, 1992). Similar results were reported by Mansaray et al. (2000) and Radmanesh et al. (2006).

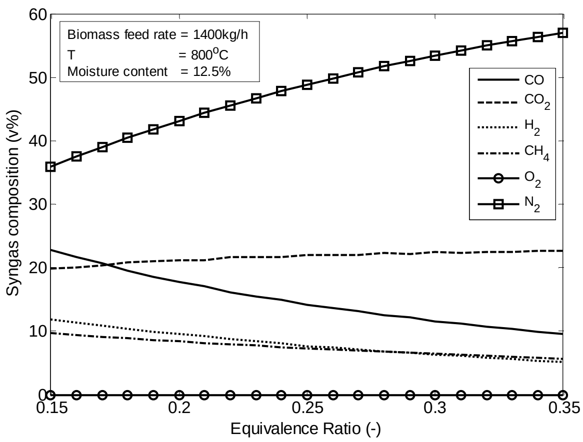

FIGURE 4 EFFECT OF ER ON SYNGAS COMPOSITION

In a self-heated gasifier, the bed temperature is mainly controlled by adjusting ER or biomass feed rate. A higher ER introduces more O_2 and enhances the degree of combustion which in turn increases the bed temperature. Therefore, bed temperature is a dependent variable in the case of biomass gasification. However, temperature has a pronounced effect on reaction kinetics and the gasifier performance is sensitive to the bed temperature change. For this reason, the bed temperature is selected to analyze its effect on the gasifier performance. Figure 5 shows the effect of bed temperature on syngas composition. The model results showed that increasing average bed temperature had a positive effect on the mole fractions

of combustible gases. Growing temperature from 650 to 900°C increased the mole fraction of CO from 10 to 18.5%, the mole fraction of H_2 from 7.2 to 9.8%, and the mole fraction of CH_4 from 5 to 8.2%, respectively.

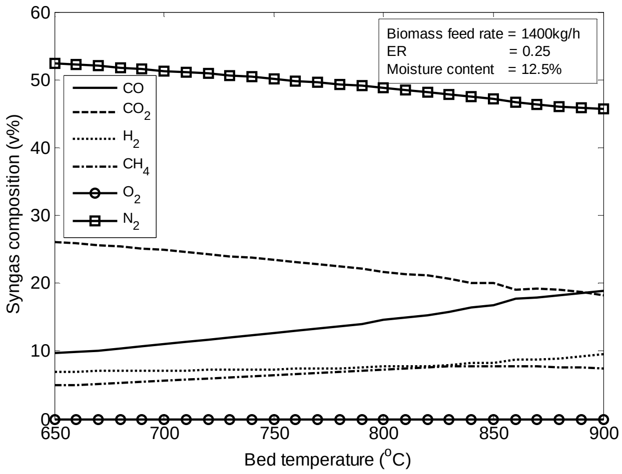

FIGURE 5 EFFECT OF BED TEMPERATURE ON SYNGAS COMPOSITION

Figure 6 shows the effect of biomass feed rate and/or fluidization velocity on the mole fractions of syngas constituents. Again, an average bed temperature of 800°C was used. Increasing the biomass feed rate and/or fluidization velocity decreased the mole fraction of CO, whereas having little effect on the mole fraction of H_2 and CH_4. This was due to following possible reasons: (a) the high amount of biomass fed into the gasifier which increased the bed inventory and (b) the shorter residence time for the char in the gasifier which resulted in the loss of some of its energy content as reported by Beaumont and Schwob (1984).

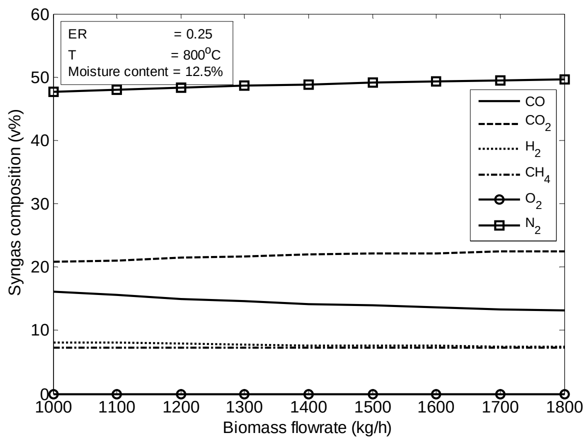

FIGURE 6 EFFECT OF BIOMASS FEED RATE ON SYNGAS COMPOSITION

Figure 7 shows the effect of biomass moisture content on the syngas composition. The model results showed that the mole fraction of CO decreased and that of H_2 increased with increasing moisture content, whereas that of CH_4 remained approximately constant. The increase in the mole fraction of H_2 and decrease in the mole fraction of CO with increment in the moisture content indicated that the water-gas reaction and CO shift reaction had a substantial effect in steam gasification. Similar results were reported by Richard et al. (1985) and Mansaray et al. (2000).

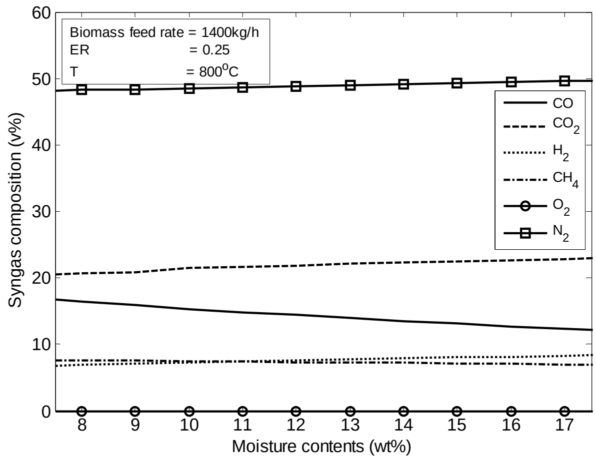

FIGURE 7 EFFECT OF BIOMASS MOISTURE CONTENT ON SYNGAS COMPOSITION

Effect of Operating Conditions on Syngas LHV

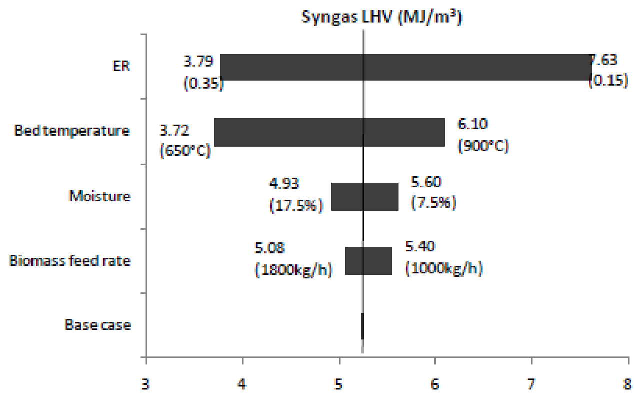

FIGURE 8 EFFECT OF OPERATING CONDITIONS ON SYNGAS LHV

Syngas LHV is the potential energy contained in the syngas if the water vapour from combustion of hydrogen is not condensed. Figure 8 is a tornado diagram showing the effect of operating conditions on syngas LHV. For each of the four parameters, the chart contains one horizontal bar and two sets of numbers, one of the left and the other to the right of the bar. Each set of numbers corresponds to the result value (upper number) and the value of the parameter at which the result value was reached (the lower number within brackets). The bar at the top of the chart has the maximum impact on the result, with each successive lower bar having a lesser impact. The vertical line corresponds to the value of the base case. The model results have demonstrated that ER has the

largest effect on syngas LHV (double from 3.79 MJ/m^3 to 7.63 MJ/m^3 while ER changing from 0.35 to 0.15), and biomass feed rate has the smallest effect. It is also indicated that the increment of bed temperature had a positive effect on syngas LHV, whereas that of ER had a negative effect.

Effect of Operating Conditions on Syngas Production Rate (SPR)

SPR, defined as syngas flowrate over biomass feed rate, indicates the speed of syngas production under certain feedstock flowrate. Figure 9 shows the effect of operating conditions on SPR. The results showed ER had the largest effect on SPR. Unlike syngas LHV, change of ER had a positive effect on SPR and it could be attributed to the increment of inert N_2. Increasing ER from 0.15 to 0.35 increased SPR from 1.32 to 1.95 m^3/kg biomass. Increasing bed temperature also benefitted syngas yield, because a higher temperature enhanced pyrolysis and endothermic gas-solid reactions and more carbon were converted to gaseous products. Biomass feed rate and moisture content had quite little effect on syngas yield.

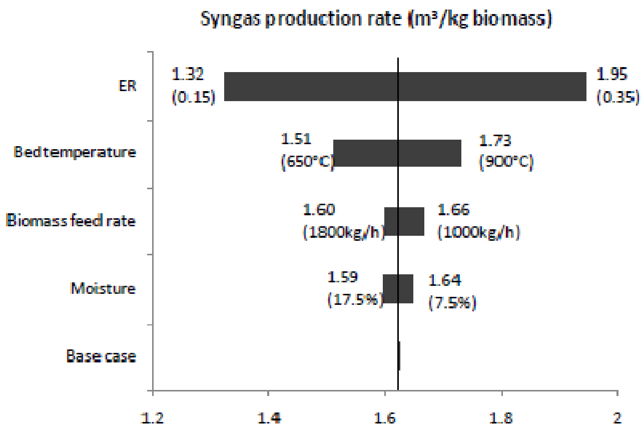

FIGURE 9 EFFECT OF OPERATING CONDITIONS ON SPR

Effect of Operating Conditions on Gasification Efficiency (GE)

GE is defined as the total energy contained in the syngas over the total energy contained in the biomass. Figure 10 shows the effect of operating conditions on GE. The model results showed bed temperature had the most important effect on GE. When increasing bed temperature from 650 to 900°C, GE increased from 38.41 to 72.16%. ER is another factor influencing GE significantly. Decreasing ER from 0.35 to 0.15 increased GE from 50.41 to 69.12%. Biomass moisture content and feed rate had relatively small influence on GE. Similar to ER, both of them had negative effect on GE.

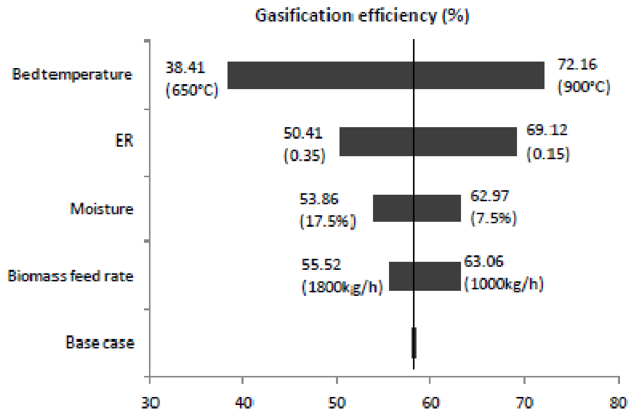

FIGURE 10 EFFECT OF OPERATING CONDITIONS ON GE

Effect of Operating Conditions on Carbon Conversion Ratio (CCR)

CCR is defined as the total carbon converted to gas phase over total carbon contents in the biomass. Figure 11 shows the effect of operating conditions on CCR. It is indicated that the most important parameter impacting CCR is bed temperature. Increasing temperature from 650 to 900°C increased CCR from 75.85 to 95.49%. Change of biomass feed rate had a negative effect on CCR. Increasing biomass feed rate from 1000 to 1800 kg/h decreased CCR from 91.27 to 85.15%. When increasing ER in the investigated range, CCR increased from 85.73 to 91.15%. Change of biomass moisture had nearly no effect on CCR.

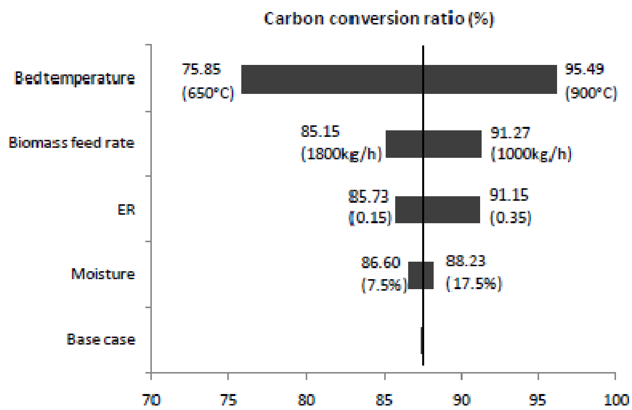

FIGURE 11 EFFECT OF OPERATING CONDITIONS ON CCR

Discussion

Equivalence ratio (ER) and superficial velocity (u_g) are measures of the air flowrate. ER is the ratio of air flow to the airflow required for stoichiometric combustion of the biomass, which indicates extent of partial combustion. u_g is the ratio of air flow to the cross-sectional area of the gasifier, which removes the influence of gasifier dimension by normalization (Radmanesh et al., 2006). Hence, both ER and u_g are directly proportional to the airflow. Air flow

influences the gasification products in several different ways. Air supplies the O_2 for combustion and affects the residence time. By varying the amount of O_2 supply, air flow rate controls the degree of combustion, which in turn affects the gasification temperature. Higher airflow rate results in higher temperature which leads to higher biomass conversion and a higher quality of syngas. An excess degree of combustion, on the other hand, results in decreased energy content of the gas produced because a part of biomass energy is spent during combustion. Higher airflow also shortens the residence time which may decrease the extent of biomass conversion. For a directly heated gasifier, air flow rate is the most important factor influencing the product quantity and quality since it affects rate of burning (hence the bed temperature) and residence time (Beaumont and Schwob, 1984).

The sensitivity analysis showed that an increased ER had a negative effect on combustible gases, syngas LHV and gasification efficiency. On the other hand, increasing ER resulted in a proportional increase of gasification temperature. This has been revealed with the findings from experimental measurements (Wang et al., 2007; Wu et al., 2009) and numerical simulation (Sett and Bhattacharya, 1988; Ergudenler et al., 1997; Mansaray et al., 2000). Gasification temperature is one of the most influential factors affecting the gasifier performance. It was shown in the sensitivity analysis that an increase in temperature had a positive effect on the syngas composition and LHV. Thus, one has to compromise between a low operating temperature leading to higher percentage of combustible gases accompanied by higher percentages of char and tar, and a high temperature that produces less char and tar but low combustible gases.

Biomass feed rate is another factor influencing the gasifier performance. Overfeeding of biomass can lead to plugging and reduced conversion efficiencies whereas starvefeeding results in less gas yield. Hence, an optimum biomass feed rate is desired for the gasification system to maximize its energy efficiency. Optimum biomass feed rate is dependent primarily on the design of the gasifier and the properties of the biomass.

Increased moisture content in the biomass feed was found to moderate the reactor temperatures. Although too much water makes the gasification temperature more difficult to sustain, as reported by Bacon et al. (1985), the reduced reactor temperature is advantageous for slagging fuels because the endothermic steam generation exposes the mineral matter of the fuel to lower temperatures and reduces slag formation. This, however, should be balanced against vaporization of water and poor ignition of wet fuel. Also, high moisture content of the feedstock increased the amount of water in the syngas and thus its sensible heat at the cost of the chemically bonded energy.

Conclusions

The model sensitivity analysis showed that ER, bed temperature, fluidization velocity, biomass feed rate and moisture content all had effects on the gasifier performance. However, the model was more sensitive to the variations in ER and bed temperature.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support from the National Science and Engineering Research Council of Canada (NSERC), the National High-tech R&D Program of China (2007AA05Z410 & 2009AA05Z434) and Chinese Academy of Sciences (KGCX2-YW-329).

REFERENCES

Bacon, D.W., Downie, J., Hsu, J.C. and Peters, J., 1985. Modelling of fluidized bed wood gasifiers. Fundamentals of Thermochemical Biomass Conversion. Overend, R.P., Milne, T.A. and Mudge, K.L. London & New York, Elsevier Applied Science: 717-732.

Beaumont, O. and Schwob, Y., 1984. Influence of physical and chemical parameters on wood pyrolysis. Industrial Engineering Chemical Process Design and Development 23: 637-641.

Ergudenler, A. and Ghaly, A.E., 1992. Quality of gas produced from wheat straw in a dual distributor type fluidized bed gasifier. Biomass and Bioenergy 3(6): 419-430.

Ergudenler, A., Ghaly, A.E., Hamdullahpur, F. and Al-Taweel, A.M., 1997. Mathematical modeling of fluidized bed straw gasifier - Part I: Model development. Energy Sources 19(5): 1065-1084.

Kumar, A., Jones, D.D. and Hanna, M.A., 2009. Thermochemical biomass gasification: A review of the current status of the technology. Energies 2: 556-581.

Mansaray, K.G., AL-Tawell, A.M., Ghaly, A.E.,

Hamdullahpur, F. and Ugursal, V.I., 2000. Mathematical modeling of a fluidized bed rice husk gasifier: Part II - model sensitivity. Energy Sources 22: 167-185.

Miao, Q., Zhu, J., Barghi, S., Wu, C., Yin, X. and Zhou, Z., 2010. Modeling biomass gasification in circulating fluidized beds: part I - model development. Submitted to Biomass and Bioenergy on Nov. 9, 2009, chapter 5 of this thesis.

Radmanesh, R., Chaouki, J. and Guy, C., 2006. Biomass gasification in a bubbling fluidized bed reactor: experiments and modeling. Enviromental and Energy Engineering 52: 4258-4272.

Raissi, A.R. and Trezek, G.J., 1987. Parameters governing biomass gasification. Industrial and Engineering Chemistry Research 26(2): 221-228.

Richard, J.R., Cathonnet, M. and Rowan, J.P., 1985. Gasification of charcoal: influence of water vapour. Fundamentals of Thermochemical Biomass Conversion. Overend, R.P., Milne, T.A. and Mudge, K.L. London & New York, Elsevier Applied Science Publishers: 589-599.

Sadaka, S.S., Ghaly, A.E. and Sabbah, M.A., 2002. Two phase biomass air-steam gasification model for fluidized bed reactors: Part II - model sensitivity. Biomass and Bioenergy 22(6): 463-477.

Sanz, Alvaro, and Jose Corella. "Modeling Circulating Fluidized Bed Biomass Gasifiers. Results from a Pseudo-Rigorous 1-Dimensional Model for Stationary State." *Fuel Processing Technology* 87 (2006): 247-58.

Schoeters, J., Maniatis, K. and Buekens, A., 1989. The fluidized bed gasification of biomass: experimental studies on bench scale reactor. Biomass 19: 129-143.

Sett, A. and Bhattacharya, S.C., 1988. Mathematical modeling of a fluidized bed charcoal gasifier. Applied Energy 30(1): 161-186.

Wang, Y., Yoshikawa, K., Namioka, T. and Hashimoto, Y., 2007. Performance optimization of two-staged gasification system for woody biomass. Fuel Processing Technology 88: 243-250.

Wu, C., Yin, X., Ma, L., Zhou, Z. and Chen, H., 2009. Operational characteristics of a 1.2-MW biomass gasification and power generation plant. Biotechnology Advances 27: 588-592.

Yamazaki, T., Kozu, H., Yamagata, S., Murao, N., Ohta, S., Shiya, S., et al., 2005. Effect of superficial velocity on tar from downdraft gasification of biomass. Energy and Fuel 19: 1186-1191.